Paper No: SCARA-1.07-6, (40)

Design and Simulation of Pitch Optimizer and Stall Protection for A Typical UAV

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Abstract

Flight dynamics of an Unmanned Aerial Vehicle (UAV) is the science of its orientation and control in three dimensions. Primary orientations include Pitch, Roll, and Yaw. The rear part of the tailplane is known as elevator control of UAV pitch. An airplane stall is an aerodynamic condition in which the airplane exceeds its given critical angle of attack and is no longer able to produce the required lift of normal flight. The main goal of this paper is to design a controller that optimizes the response speed of pitch control and design stall protection for a typical UAV. This protection system operates according to certain conditions, which are known stall conditions. When UAV reaches these conditions, the system generates a warning that UAV is at stall point and the pilot must adjust the situation to stabilize UAV. A PID controller has been implemented on MATLAB, also mathematically calculations were done to obtain suitable PID gains for a faster and accurate response of UAV elevator, after that, these mathematically PID gains have been applied to MATLAB/Simulink. Results showed the control parameters improved, such that settling time is 4.6220 seconds, the rise time is 0.2788 seconds, the percentage overshoot is 36.8192%, and steady-state error less than 2%.

Key words-*UAV; Pitch; Stall; Optimize; Stall protection; PID*

I. Introduction

UAV getting more and more important with its increasing demand in war, now each country pays more attention to researching the work of UAV, includes early researching projects, medium-term hardware simulation, performance validation, and simulation training. All the above-mentioned need simulation research. UAV plays a more and more important role in modern ware, which is a new form [1]. Nowadays, UAV design depends heavily on the automatic control system to monitor and control many of its subsystems. UAV pitch is rotation about a sideways horizontal axis which causes an up-down movement of the nose measure by the angle of attack [2]. The main principle of flight dynamics is control and stability of aircraft's rotation about its three axes. Most essential among these rotations is the pitch which can be controlled by the elevator. Pitch angle is controlled by the angle and lift force of the elevator [3]. Most UAVs employ PID controllers for adequate control, this means that a well-tuned PID to acceptable extent can be applied to control UAVs [4].Several works have been done in the field of optimizing pitch systems to prevent a stall. Ref [2], proposed a classical PID controller to optimize pitch control system performance, results showed that the controller successfully designs [2]. Artificial Neural Networks (ANN) algorithm proposed to predict, recognize and prevent stall occurrence by [5], results demonstrate that ANN algorithm able to restore UAV from a stall [5]. Stall prevention control of UAV using feedback linearization algorithm carried out by [6], results prove algorithm robustness [6]. This work proposed a PID controller to optimize pitch speed response to prevent UAV stalls and designed a stall detection and warning system.

II. Method

Firstly, Zagi UAV model was studied, and the linearized longitudinal model considered, then this model was used to design pitch control with aid of PID controller. Finally, Stall Detection and Protection System was designed.

A. UAV Model

Equations governing UAV motion can be classified into longitudinal and lateral equations. Longitudinal equations describe longitudinal motion in the longitudinal or pitching plane under steady-flight conditions while lateral equations describe motion about the lateral plane.

B. Linearized Longitudinal Equation of Motion

UAV longitudinal dynamic can be expressed in the state-space form 1.

$$\left.\begin{aligned}\dot{x}(t) &= Ax(t) + Bu(t),\\ y(t) &= Cx(t) + Du(t),\end{aligned}\right\} \tag{1}$$

Where: $\dot{x}$ is state variables, for longitudinal $\dot{x} = [\mu\alpha\rho\theta]$ which

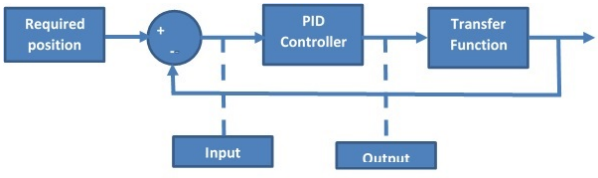


Fig. 1. Scatter diagrams using MMA.

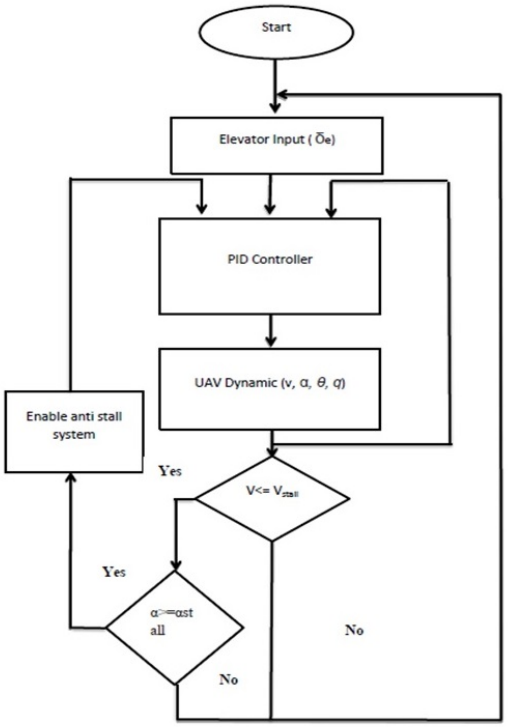


Fig. 2. Scatter diagrams using MMA.

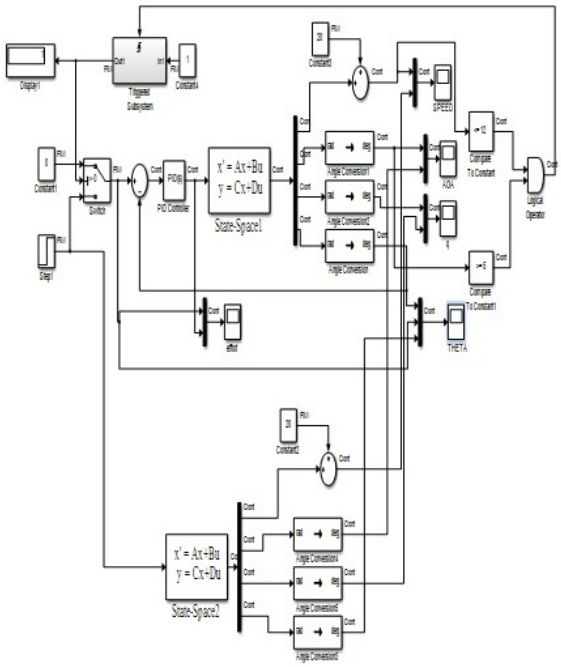


Fig. 3. Scatter diagrams using MMA.

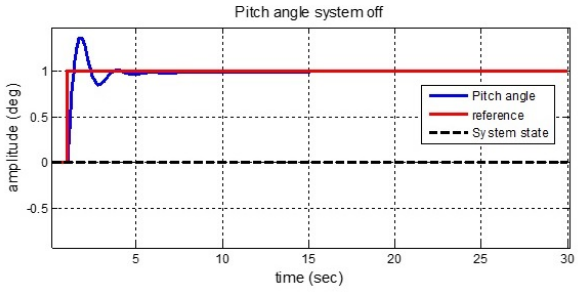


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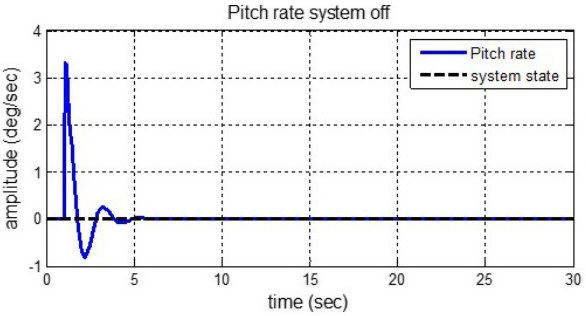


Fig. 5. Scatter diagrams using MMA.

are longitudinal speed, side slip angle, pitch rate, and pitch angle respectively. $u(t)$: is input variables, which is elevator angle. $y(t)$: is the output variables.

A: is the state matrix. B: is input matrix. C: is output matrix. D: is a direct transmission matrix.

Linearized time-invariant model of a fixed-wing UAV Zagi is given by:

$$A = \begin{Bmatrix} -0.1300 & -0.880 & 0 & -9.8066 \\ -0.607 & -7.5460 & 1.0000 & 0 \\ 0 & -147.4000 & -11.5260 & 0 \\ 0 & 0 & 1.0000 & 0 \end{Bmatrix} \quad (2)$$

$$B = \begin{Bmatrix} 0 \\ 0.0136 \\ 3.4000 \\ 0 \end{Bmatrix}, C = \begin{Bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{Bmatrix}, D = 0$$

C. Mathematically Pitch Control Design

Fig. 1 showed a general block of a pitch control system using PID, as well as, optimize pitch response speed. PID controller model is given by:

$$PID(s) = k_p + \frac{k_1}{s} + k_d S = \frac{k_d s^2 + k_p S + k_i}{S} \quad (3)$$

Where: K_d: is derivative parameter. K_i: is integral parameter. K_p: is proportional parameter. PID controller parameters calculated mathematically to control, and enhance the response speed of pitch to ensure no stall condition occurs during control action, suitable derivative values are found to be: $k_d = 0, k_p = 0.2617, k_i = 1.676$

$$PID(t) = 0.2617e + 1.676 \int_0^t e(t)dt \quad (4)$$

Stall Detection and protection system SDPS continuously protect UAV from the stall as shown in the flowchart presented in Fig. 2.

Fig. 3 presented the overall system of controlling pitch motion, and optimize response speed, as well as, stall protection

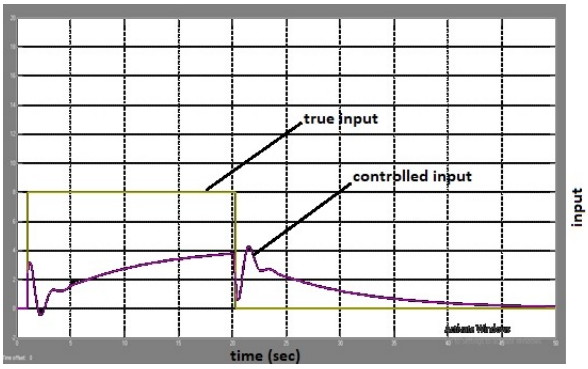


Fig. 6. Scatter diagrams using MMA.

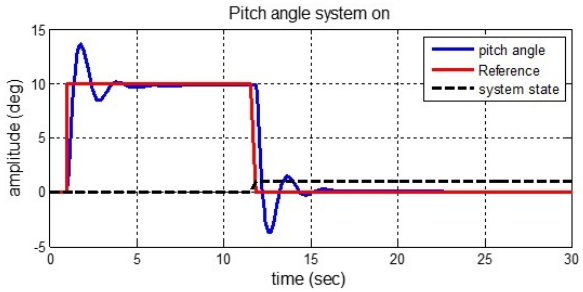


Fig. 7. Scatter diagrams using MMA.

and warning system modeled on MATLAB/Simulink. Overall designed system consists of electronics components chosen for best pitch response speed.

1) Step Unit: is the source of the system.
2) Gains: show the relationship between input and output magnitudes.
3) PID: as before, consists of three parameters calculated mathematically.
4) State Space Model: is the linearized Zagi model.
5) Angle Convertor: this unit converts degree to radian.
6) Angle of Attack (AoA) Sensor: used to sense any change of AoA.
7) Airspeed Sensor and Display: used to sense any change of UAV airspeed and tuned to lowest permissible value before stall can occur.
8) Pitch Angle Display: used to display and observe pitch angle value.
9) Relational Operator: used to comparison minimum permissible airspeed and actual UAV airspeed, as well as, comparing real UAV angle of attack and maximum permissible angle of attack.
10) Logic Operator: used to generate stall warning when stall condition met, it is simply AND logic gate takes input from two relational operators and single output fed to switch.
11) Switch: the purpose of the switch is to open or close the control circuit; when the control circuit is opened no current will flow and Vis versa.
12) Triggered Subsystem: it receives AND gate output, and adjusts the situation according to the received signal.
13) Display: used to indicate activation of SDPS.

TABLE I
STALL CONDITIONS AND RESULTS..

Unit step final value	The angle of attack ¿= 50	Airspeed ¡= 12 m/s	SDPS output	activation
1	0	0	0	OFF
3	0	0	0	OFF
5	0	0	0	OFF
7	0	1	0	OFF
8	1	1	1	ON
10	1	1	1	ON
11	1	1	1	ON
12	1	1	1	ON

D. Stall Detection and Protection System (SDPS) Design

SDPS designed to operate according to the final value of step input signal experimentally, when final value between 1 and 7 system not activate. The system activates only when the final value of the input step signal is greater than or equal to 8. Stall conditions are the angle of attack greater or equal to maximum permissible value, and airspeed less than or equal to minimum permissible value. SDPS activated only when these two conditions are met together. SDPS designed to work continuously throughout UAV flight, when stall conditions whenever happened the system warning operator and automatically adjusts UAV to avoid a stall. Table (I) showed SDPS activation due to stall conditions.

III. Results and Discussion

Results obtained from simulation of designed PID controller and SDPS in MATLAB. Table (II) presents the dynamic characteristic of the designed system. Dynamic characteristics showed that the rise time of the controlled system is greater than an original system which demonstrated the response of the original system is faster than the controlled one. The response speed of the controlled system is suitable and demands no stall can occur. Also, other characteristics proved enhancement of settling time, overshoot, undershoot, and peak values. Fig. 4 illustrated pitch angle response.
Fig. 5 showed pitch rate response (speed response), it is clear that the original system (open loop) pitch rate started to increases to magnitude greater than permissible values which lead to a stall, and takes a long time to stabilize. While controlled system increased to values less than stall permissible value and stabilized faster.
When input final value greater than allowable input, SDPS activated due to existence of stall conditions, fig. 6 presented true input for this case with and without PID. The input controlled

TABLE II
DYNAMIC CHARACTERISTIC OF THE DESIGNED CONTROLLER.

Specification	Open-loop system	Closed-loop system
Rise Time	0.2639	0.2788
Settling Time	81.0073	4.6220
Settling Min.	-4.5203	0.8423
Settling Max0	10.1245	1.3682
% Overshoot	435.9756%	36.8192%
Undershoot	239.2959	0
Peak	10.1245	1.3682

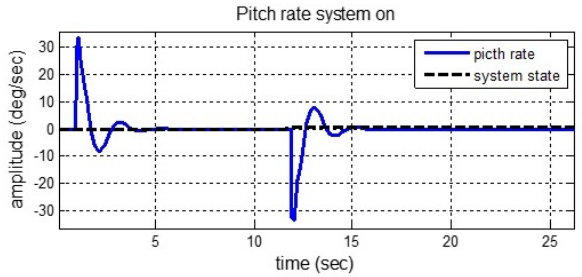


Fig. 8. Scatter diagrams using MMA.

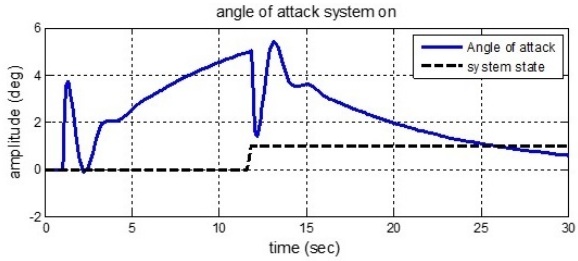


Fig. 9. Scatter diagrams using MMA.

by PID and SDPS to prevented stall. SDPS and PID adjusted the input to a value less than stall input which is 4.26, while true input reached the stall condition 8. Response of pitch angle presented in fig. 7, showed that pitch angle increased, settled, and decreased which indicates stall occurrence, when pitch angle exceeds permissible value SDPS adjust PID to stabilized UAV automatically. The peak value of pitch angle during the stall is 10.9419 deg. Which is greater than the peak value during un-stall. Also. Stall percentage overshoot is 36.7735%, which same as un-stall percentage overshoot, settling time, peak time, and rise time remained fixed.

Pitch rate behavior is shown in fig. 8. As presented, pitch rate increased to $300/sec$, after that settled and system became stable for few moments, and decreased after, pitch rate continued increased and decreased, and SDPS adjusted UAV.

UAV angle of attack when input exceeded permissible values which leads to stall condition illustrated in fig. 9. The response curve of the fig. 9 concluded that the angle of attack started to increase for a value greater than allowable, then decreased and increased, which indicated stall condition activated SDPS to stabilize UAV.

IV. CONCLUSION

UAV pitch angle and pitch rate are required to be maintained at the desired value to prevent a stall. This work goal is to design a pitch response optimizer, and Stall Detection and Protection System (SDPS) to ensure no stall condition happened under different conditions. First of all PID controller was designed to optimize the pitch and pitch rate of Zagi UAV, also, SDPS designed to detect and protect UAV from the stall, and finally, PID controller integrated with SDPS. The overall system simulated on MATLAB/Simulink, results obtained showed that designed PID controller relatively gave better performance for UAV stall detection and protection, furthermore, results analysis demonstrated that settling time, percentage overshoot, steady-state error, and rise time was greatly improved.

V. RECOMMENDATIONS

For further improvements ,a model and extensive test to the proposed system in Hardware using loop simulation is need to be conducted.

ACKNOWLEDGMENT

This work was supported by Karary University. The authors would like to thank the department of aeronautical engineering at Karary University for their continuous help and support

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